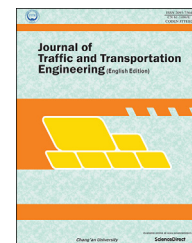


Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jtte

Original Research Paper

Thermal segregation of asphalt material in road repair



Juliana Byzyka^{*}, Mujib Rahman, Denis Albert Chamberlain

Institute of Energy Features, Department of Mechanical Aerospace and Civil Engineering, Brunel University London, Middlesex UB8 3PH, United Kingdom

HIGHLIGHTS

- Thermal segregation is developed in patching in both winter and summer seasons.
- Long haulage time of HMA progresses thermal segregation.
- Poor insulation measures of HMA during transportation raises thermal segregation.
- Poor compaction and low interface bonding adversely affect patching performance.
- Pothole repairs prematurely fail at cold spots and poorly bonded repair edges.

ARTICLE INFO

Article history:

Received 28 September 2016

Received in revised form

3 May 2017

Accepted 4 May 2017

Available online 14 July 2017

Keywords:

Hot mix asphalt

Pothole

Patch repair

Thermal segregation

Thermography method

ABSTRACT

This paper presents results from a field study of asphaltic pavement patching operations performed by three different contractors working in a total of ten sites. It forms part of an ongoing research programme towards improving the performance of pothole repairs. Thermal imaging technology was used to record temperatures of the patching material throughout the entire exercise, from the stage of material collection, through transportation to repair site, patch forming, and compaction. Practical complications occurring during patch repairs were also identified. It was found that depending on the weather conditions, duration of the travel and poor insulation of the transported hot asphalt mix, its temperature can drop as high as 116.6 °C over the period that the reinstatement team travel to the site and prepare the patch. This impacting is on the durability and performance of the executed repairs. Cold spots on the asphalt mat and temperature differentials between the new hot-fill asphalt mix and existing pavement were also identified as poorly compacted areas that were prone to premature failure. For example, over the five-minute period, the temperature at one point reduced by 33% whereas the temperatures of nearby areas decreased by 65% and 71%. A return visit to the repair sites, three months later, revealed that locations where thermal segregation was noted, during the patching operation, had failed prematurely.

© 2017 Periodical Offices of Chang'an University. Publishing services by Elsevier B.V. on behalf of Owner. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

^{*} Corresponding author. Tel.: +44 7475 71 9051.

E-mail addresses: juliana.byzyka@brunel.ac.uk (J. Byzyka), mujib.rahman@brunel.ac.uk (M. Rahman), denis.chamberlain@brunel.ac.uk (D. A. Chamberlain).

Peer review under responsibility of Periodical Offices of Chang'an University.

<http://dx.doi.org/10.1016/j.jtte.2017.05.008>

2095-7564/© 2017 Periodical Offices of Chang'an University. Publishing services by Elsevier B.V. on behalf of Owner. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

A road network constitutes an important asset of developed countries such as the UK. It contributes to the economic and social well-being at all levels. Among the three types of pavements, asphalt pavement is the most usual type of pavement in the UK commencing 95% of the road network. Even though the asphaltic surfacing of an asphalt pavement is designed to be a less permeable layer compared to other layers of a pavement structure (aggregate sub-base, capping, and subgrade), water does permeate into it. The ingress of water into the pavement deteriorates the mastic and the aggregate mastic-bond causing. In combination with traffic loading, initial stripping rapidly leads to very serious ravelling and then to the creation of potholes (Dawson, 2008; Thom, 2008; Adlinge and Gupta, 2013). Prolonged cold wet weather period with cyclic freeze-thaw conditions, such as occurring in the UK, accelerates pothole development and causes high maintenance costs.

Over recent years, the use of high-quality materials, that will protect the surface layer of the asphalt pavement from weather conditions and high traffic loading, has been tried (Texas Department of Transportation, 2011). However, increasing traffic volumes and heavier loads, allied with repeated adverse weather are causing significant deterioration of the UK road network, resulting in millions of potholes and failed areas (cracking, stripping, and ravelling). The Automobile Association (AA) survey, where more than 22,000 people participated, revealed that the 33% of participants have confronted damage to their vehicles due to potholes on roads. In 2012, the number of potholes, which has grown with the passage of the years, was found to have increased up to 30% (Knapman, 2013).

The situation is not improving. According to the AA report in 2014, road deterioration in the UK had risen to 40% by March 2014 in comparison with October 2013 figures (The Automobile Association (AA), 2016). The annual local authority road maintenance (ALARM) report in 2015 (Asphalt Industry Alliance, 2015) confirms also an increase in potholes. The poor riding condition of UK roads has generated significant public dissatisfaction as road distress does not only create dangerous driving conditions but also high repair bills for their vehicles.

Even when road distresses are repaired a number of them fail within few years (Rahman and Thom, 2012). Usually, the reasons for this failure are because (a) the patching material is laid on failed areas and it is likely that the underlying materials are in poor condition, (b) the quality of the repairs offered by the contractor differs with the skill levels of the teams responsible for the repairs varies, and (c) the variable quality of patch repairs. Other reasons that confirm the failure of road maintenance are the lack of technical quality due to not established guidelines or test methods, inadequate compaction, poor surface preparation and overall inferior workmanship, as well as the lack of appropriate guidelines for maintenance engineers on materials suitability in every patch repair situation.

Potholes are repaired by two main methods named as pothole filling and pothole patching. The former is mainly

considered as a temporary repair whilst pothole patching is a more permanent repair operation (Lavin, 2003). Pothole patching usually includes marking of the area around the pothole which indicates the material to be removed from the existing pavement, cutting off the old asphalt and removal, cleaning of the pothole excavation from debris and water, tack coat application for bonding of the existing pavement with new fill material and compaction (Anderson and Thomas, 1984; Lavin, 2003; Thom, 2008). The fill material, in the case of pothole patching, is usually hot mix asphalt (HMA). Thus, inappropriate levels of mix temperature will affect patching performance. If the temperature of HMA falls below the cessation temperature, no further compaction can occur (Hartman et al., 2001; Delgadillo and Bahia, 2008; Kloubert, 2009; Watson et al., 2010). Insufficient compaction leads to reduced density of HMA surface resulting in possible future premature failure (Thom, 2008).

Main causes of pothole patching failures are the mode of transportation of HMA between production plant and paving site, segregation, inappropriate compaction, low interface bonding between pothole excavation and hot-fill material, and pothole geometry preparation. Among the referred patching causes, segregation is of most concern in this study. Segregation is usually categorised into aggregate segregation and thermal segregation. The former is defined as the non-uniform distribution of coarse and fine aggregates in the asphalt matrix whilst thermal segregation is described as cold spots in the HMA mat (Stroup-Gardiner and Brown, 2000).

In comparison with aggregate segregation, thermal segregation cannot be visually identified by the human eye. However, a suitable, well-defined method is infrared thermography (Davis, 2012). This is able to recognize and measure the thermal energy emitted from an object that is not possible with the human eye (FLIR Systems AB, 2011).

2. Research objectives

The key objective of this research is to evaluate the extent of thermal segregation in HMA road patch repairs executed by three independent teams of workers (designated contractors A, B and C) operating in different weather conditions, methods of transportation and repair processes, and observe the outcomes after three months. It is also intended to identify possible shortcomings in current heated patch repair practices, which are failing to deliver durable outcomes.

The research involves (a) temperature monitoring during material transportation, (b) temperature monitoring during material placement and after compaction, and (c) the collection of temperature differences from several locations over the repair mat. Infrared thermography and a contactless handheld thermometer were used to gather temperature data. Observations were made for five sites in the case of Contractor A and one and four sites in the case of Contractors B and C, respectively. A return visit was made to each of these sites three months after the patching operations.

Through examining the activity of the three road repair contractors, the research is intended as a contribution towards understanding the realities of patch repair work, especially repair material heat loss and the possible

implications of this for repair performance. The adopted approach is purely observational, with no attempt to interfere or alter any aspect of the contractors' work methods or processes in the handling or use of materials. The amount of information gathered on each repair site was, unfortunately, restricted to the fast repair work needed to be followed by the crew.

3. Research methodology

To accumulate data for analysis and evaluation regarding the causes of thermal segregation and how possible failure modes are likely to occur, three contractors (Contractors A, B and C) were followed during their patch repair procedure at different locations in the UK. The temperature of the HMA was monitored commencing from the material production plant through the laying and the compaction of the material on each repair site. For each repair site, the surface temperature was collected using a calibrated thermal imaging camera model FLIR B200, having a resolution of 0.08 °C.

The field investigation relating to Contractor A was conducted in December 2014. Five different patch repair assignments were monitored, these all located in an urban environment, addressing residential or busy major roads. The maintenance of all sites was completed in one day between 9:30 a.m. to 15:10 p.m. with air temperature approximately 4 °C and wind speed 2.2 m/s. The patch area and depth ranged between 1 m²–3 m² and 0.04 m–0.05 m respectively. Appropriate pothole geometry preparation was followed by the crew except for the use of tack coat prior to pothole filling. The newly laid repair material was compacted using both plate compactor (known else as Wacker plate) and roller compactors.

The field investigation relating to Contractor B was conducted in January 2014. Only one project was monitored. The road repair was conducted in an urban area on a busy major road. The maintenance was completed between 10:20 a.m. to 12:45 p.m. The air temperature was approximately 4 °C and wind speed is 3.6 m/s. The area and depth of the patch repair were 13.4 m² and 0.06 m respectively. The patch to be reinstated was along the drainage path of the road with a large

amount of water flowing through it. This impacted on proper preparation of the pothole excavation in that was not possible to apply tack coat to the pothole. The newly laid repair material was compacted using both plate compactor and roller compactors.

The field investigation relating to Contractor C was monitored during its patch repair process on a major busy road in an urbanized area and three residential roads of a rural environment. The patch repairs were completed in August 2015 in two different days (two repairs per day). The maintenance on the repair sites 7 and 8 was completed between 8:00 a.m. to 15:00 p.m. and on the repair sites 9 and 10 between 10:00 a.m. and 13:00 p.m. The air temperature at repair sites 7 and 8 ranged between 15 °C–18 °C and 21 °C–22 °C at repair sites 9 and 10. The wind speed was 4.9 m/s in each case. The depth of the patch repair, using HMA, ranged between 0.05 m and 0.06 m, which was compacted using only plate compactor. The crew of Contractor C was the only ones that used tack coat for all four repair operations.

Further, all three contractors used a type of end dump truck to transport the asphalt material from the production facilities to the locations of the repair sites (Fig. 1). After the material was loaded into the truck it was covered by an insulating sheet. They all used the same uncontrolled process of transportation. The described data are presented in Table 1.

4. Observations in the repair activity

4.1. Effect of transportation method

The transportation method of HMA is a key factor to study when thermal segregation is to be monitored. Usually, asphalt material is prepared at the asphalt plant and then by using an appropriate vehicle is transported to the paving site. It is during this stage where a great amount of aggregate and thermal segregation is detected on asphalt (Bode, 2012). There are three usual types of vehicle for asphalt transportation named as end dump, bottom dump or belly dump, and live bottom or flo-boy. The design of the three truck types is aimed to maintain asphalt temperature and quality from the

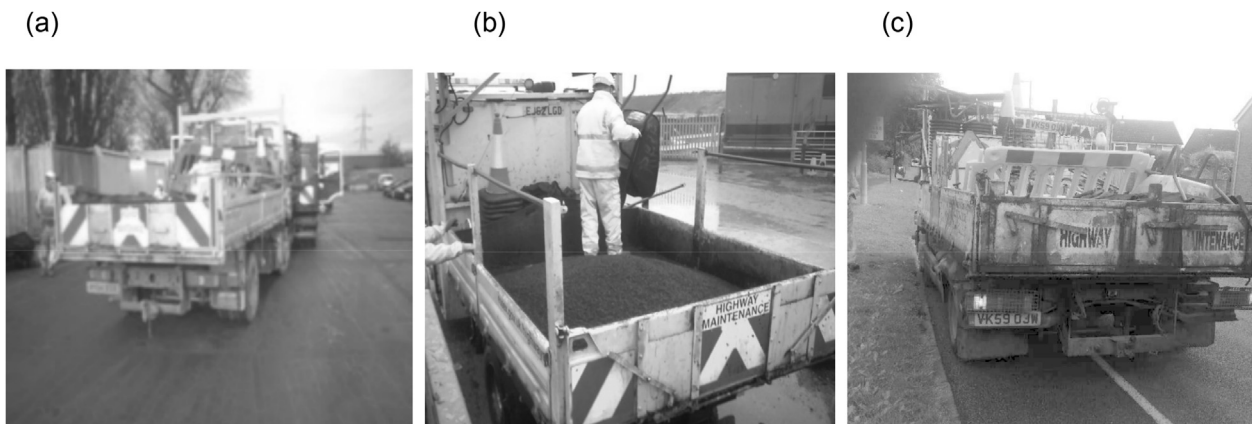


Fig. 1 – Mode of HMA transportation. (a) Contractor A. (b) Contractor B. (c) Contractor C.

Table 1 – Patch repair data of Contractors A, B and C.

Contractor	Repair site No.	Repair time															Pothole geometry		Repair method					
			Urban area	Rural area	Busy major road	Residential road	Winter ^a	Summer ^b	Wind speed (m/s)	Patch area (m ²)	Patch depth 0.04 m	Patch depth 0.05 m	Patch depth 0.06 m	End dump truck	HMA loading mat temperature range (°C)	HMA mat temperature range prior to repair (°C)	Existing pavement temperature (°C)	Water	Debris	Vertical faces	Tack coat application	Pothole filling	Patching	Plate compactor
A	1	9:30 a.m.–	✓		✓	✓		2.2	3.0				✓	69–150	69–143.5	1	Removed	Removed	✓			✓	✓	✓
	2	15:10 p.m.	✓		✓	✓			2.0		✓	✓			67–132				✓			✓	✓	✓
	3		✓			✓	✓		1.5	✓		✓			63–128				✓			✓	✓	✓
	4		✓			✓			1.0	✓		✓			60–95				✓			✓	✓	✓
	5		✓		✓	✓	✓		2.0	✓		✓			55–90				✓			✓	✓	✓
B	6	10:20 a.m.– 12:45 p.m.	✓		✓	✓		3.6	13.4		✓	✓		75–142	55–100	7	Present during repair	Removed	✓			✓	✓	✓
C	7	8:00 a.m.–	✓		✓		✓	4.9	N/A		✓	✓	✓	85–158.3	80–142.5	19	Removed	Removed	✓	✓		✓		✓
	8	15:00 p.m		✓		✓	✓				✓		✓		39.4–41.7	21				✓	✓	✓	✓	✓
	9			✓		✓	✓				✓		✓	100–138.5	80–133.7	20				✓	✓	✓	✓	✓
	10			✓		✓	✓					✓	✓		65–122	21				✓	✓	✓	✓	✓
Note:																								
^a Contractor A all sites: 4 °C (on-site measurement), Contractor B 4 °C (from MET office).																								
^b Contractor C site 7 and site 9: 15 °C–18 °C, site 8 and site 10: 21 °C–22 °C (on-site measurements).																								

time that is received at the production plant to the repair site. The vehicle used during the observations in this study, for all three contractors, was a type of end dump truck (Fig. 1).

The way that the material is dropped in the transportation vehicle has a huge impact on the extent of aggregate segregation. Therefore, dropping the material onto the vehicle in one batch is less preferred than in smaller masses. However, this research is more concerned with thermal segregation and, therefore, the effect of aggregate segregation is not studied in more detail, although not ignored. To this extent, it was observed that Contractors A and B loaded asphalt onto the truck in one batch whereas Contractor C loaded asphalt in two batches. However, the truck beds were adequately cleaned and lubricated.

4.1.1. Contractor A

During transportation, the HMA was covered only with a thin insulation sheet (Fig. 2(a)). Two thermal images were taken immediately after the HMA was loaded onto the truck. At this point, thermal segregation had begun to develop, this shown as black areas on Fig. 2(b). The temperatures of the asphalt mat at this stage varied between 69 °C and 150 °C, indicating cold spots throughout the asphalt mat. Further, heat loss occurred through the panels of the truck and the cover sheet (Fig. 2(c)). The dark areas on the periphery of both thermal images are the surroundings to the HMA containment and not the material itself.

The asphalt with Contractor A was transported to five different repair sites with a significant distance from the

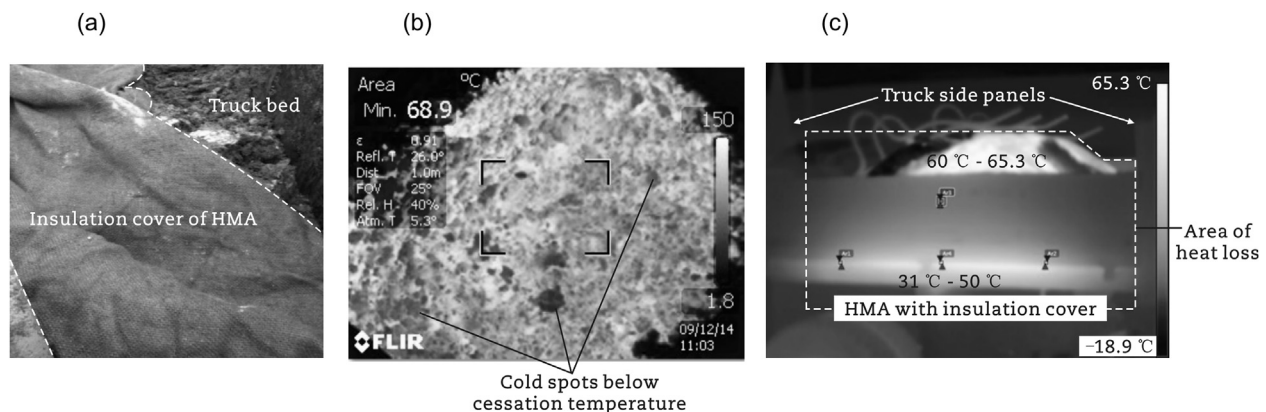


Fig. 2 – Asphalt collection at the production plant for repair sites 1–5. (a) Insulation cover of HMA. (b) Asphalt mat temperatures after collection. (c) Insulation cover temperatures.

production facility. Improper insulation of the hot-fill material and long travel time, in combination with low ambient temperatures, impacted on the asphalt mix temperature causing significant temperature losses through the panels of the truck and the cover sheet (Fig. 2). Table 2 and Fig. 3 present the overall transportation time and temperature drop versus time respectively of the asphalt from the production plant to each repair site.

There was an initial drop at temperature of 6.5 °C after 50 min of transportation between the asphalt plant and the first repair site. An overall drop of 60 °C occurred between the initial temperature of 150 °C and the delivery temperature on the last repair site, after 7 h and 25 min. A dramatic temperature difference of 33 °C occurred between repair sites 3 and 4 with the asphalt mat reaching 95 °C. This was a reduction of approximately 37% from the initial temperature of 150 °C. Asphalt temperature decreased by 40% between the asphalt plant and the last repair site.

4.1.2. Contractor B

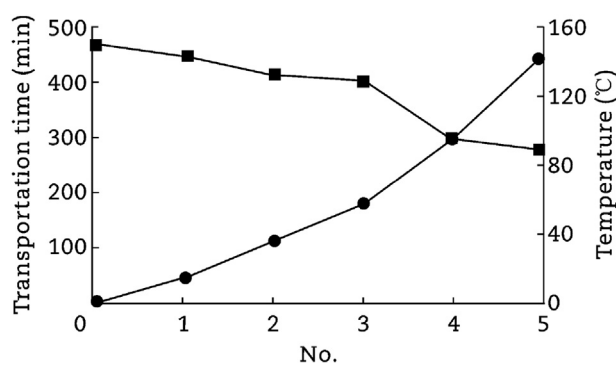
Contractor B was monitored during their patch repair activity on repair site 6, between the production facility and this. The transportation process of Contractor B is similar to that of Contractor A. A tail gate dump truck type was used to transport the HMA. When the asphalt was loaded onto the truck it was covered by an insulation sheet. The prevailing ambient temperature was approximately 4 °C. Three thermal images of the asphalt were taken immediately after loading the HMA onto the truck, these are all shown in Fig. 4.

Maximum and minimum mat temperatures were determined from the thermal image shown on Fig. 4(a), indicating temperatures of 142 °C and 75 °C respectively. Therefore, notable heat loss and thermal segregation had started to develop. Further, Fig. 4(b) and (c) demonstrates heat loss from the joints, at the back, and alongside the transportation vehicle.

The crew travelled approximately 2 h to reach the repair site. This caused a temperature drop of 42 °C compared to the initial maximum temperature of 142 °C.

4.1.3. Contractor C

Four patch repair assignments were followed for Contractor C. An end dump truck was used to transport the asphalt from the production facilities to all repair sites. For this, refer to Fig. 5(a) and Fig. 6(a) for sites 7–8 and sites 9–10, respectively. Four patch repairs were completed in two days with repair sites 7 and 8 being finished on the first day. On each occasion,



● Transportation time (min)					
0	50	115	180	295	445
■ Temperature (°C)					
150	143.5	132	128	95	90

Fig. 3 – Asphalt temperature variation and transportation time between asphalt production facility and each repair site.

asphalt was gathered once and kept during the whole patch repair process scheduled for that day. Further, for Contractors A and B, asphalt was covered with an insulated sheet. The pothole repairs were all completed in the summer, in contrast with the other two contractors that were completed in the winter, and therefore the maximum temperature during morning maintenance (repair sites 7 and 9) was 18 °C, whereas after 12:00 p.m. the maximum temperature reached 22 °C (Table 1).

The maximum temperature of asphalt, when gathered from the production plant at day 1, was approximately 158.3 °C (Fig. 5(b)). Thermal segregation had started to develop as observed with Contractors A and B. Heat loss from the truck panels and insulation cover was also observed, shown in Fig. 5(c). At day 2, the maximum temperature measured on the mat of the HMA was 138.5 °C with cold spots also seen throughout the asphalt mat as per all the repairs previously discussed Fig. 6(b). Further, Table 3 and Fig. 7 demonstrate transportation time and temperatures of the mix upon arrival at repair sites.

As the results show, during the transportation of the HMA at day 1 there was an overall dramatic decrease of asphalt mixture temperature of 116.6 °C. This heat loss is attributed to the travelling time and uncontrolled insulation of the hot material. At day 2, the overall maximum temperature drop was much less, reaching a difference between asphalt plant and last repair site of 16.5 °C.

4.2. Effect of compaction

Compaction is a second key factor that plays a major role in the strength and performance of HMA. Ineffective compaction at reduced temperatures can have a detrimental effect on the performance of repaired asphalt surfacing. To investigate this, thermal images were taken after the compaction of the asphalt from all three contractors.

Table 2 – Asphalt transportation time between production plant and each repair site location.

No.	Location	Transportation time (min)				
0	Asphalt plant					
1	Repair site 1	50				
2	Repair site 2		115			
3	Repair site 3			180		
4	Repair site 4				295	
5	Repair site 5					445

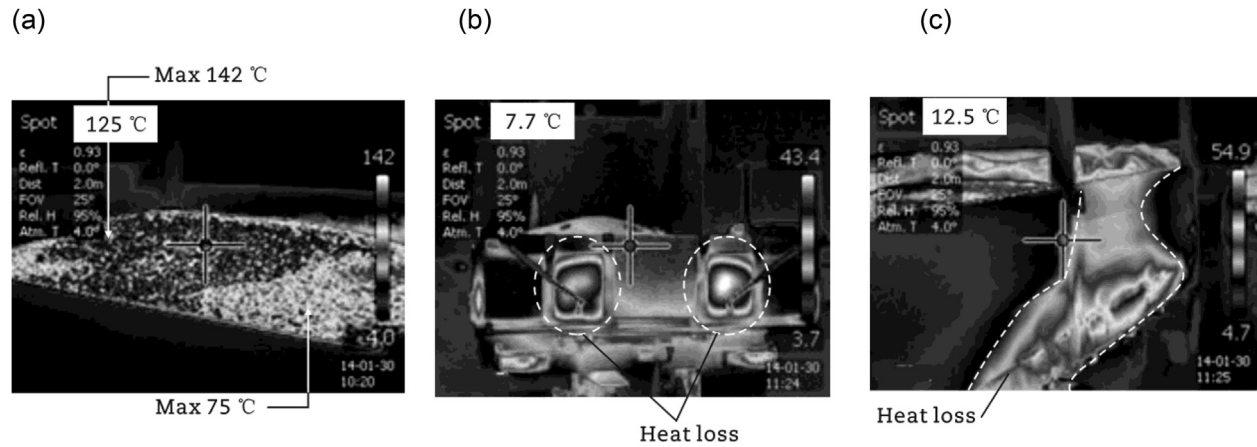


Fig. 4 – Asphalt collection at the production plant for repair site 6. (a) Temperature variation of HMA after collection. (b) Heat loss from the back of the truck. (c) Heat loss alongside the vehicle.

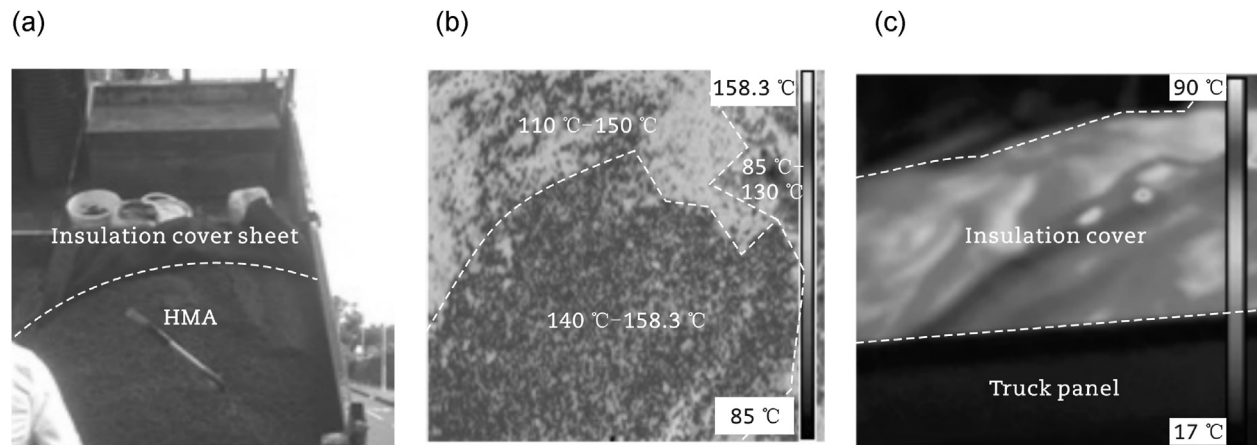


Fig. 5 – Asphalt collection at the production plant during the first day of repairs for sites 7–8. (a) Transportation truck with HMA. (b) Asphalt mat temperatures after collection. (c) Insulation cover temperatures.

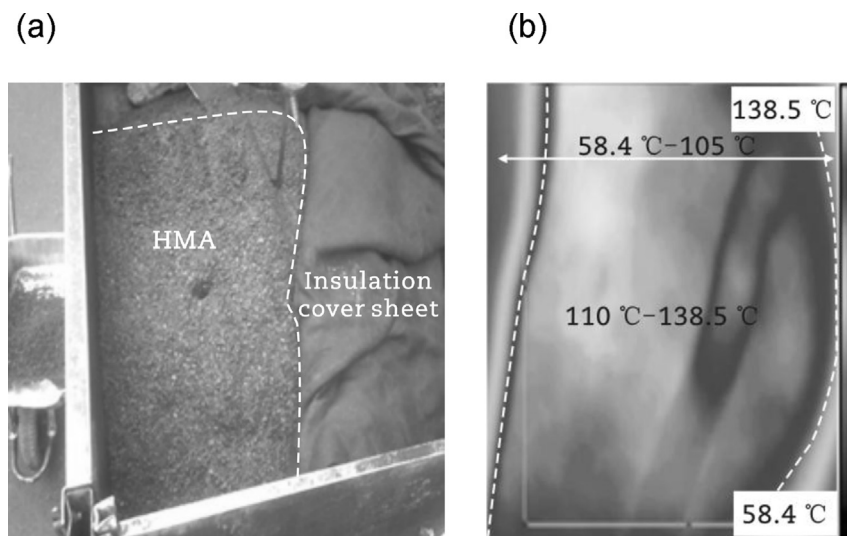


Fig. 6 – Asphalt collection at the production plant during the second day of repairs for sites 9–10. (a) Transportation truck with HMA and insulation cover. (b) Asphalt mat temperatures after collection.

Table 3 – Asphalt transportation time between plant and each repair project.

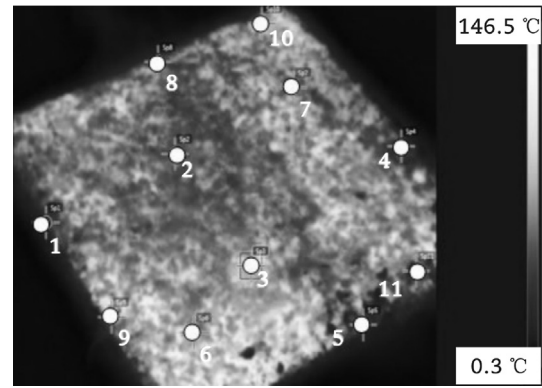
No.	Location	Transportation time (min)	
Day 1			
0	Asphalt plant	45	360
1	Repair site 7		
2	Repair site 8		
Day 2			
0	Asphalt plant	40	210
3	Repair site 9		
4	Repair site 10		

4.2.1. Contractor A

For Contractor A, Figs. 8 and 9 were taken after compaction of the HMA at repair site 1. Fig. 8 presents eleven points taken randomly on the mat. The maximum temperature of the compacted hot fill mix surface was 146.5 °C. The point temperature measurements show cold spots throughout the whole surface of the repair (Fig. 8 and Table 4) that had reached and decreased below cessation temperature indicating the areas that are most likely to prematurely fail. These were also expected to have affected the effectiveness of the compaction.

Fig. 9 shows temperature variations between the host pavement and the new hot-fill material. Eight points were chosen from the edge of the patch repair. All showed temperatures are below the cessation temperature (Table 5), indicating low strength interface bonding, prone to water ingress and premature failure under traffic loading.

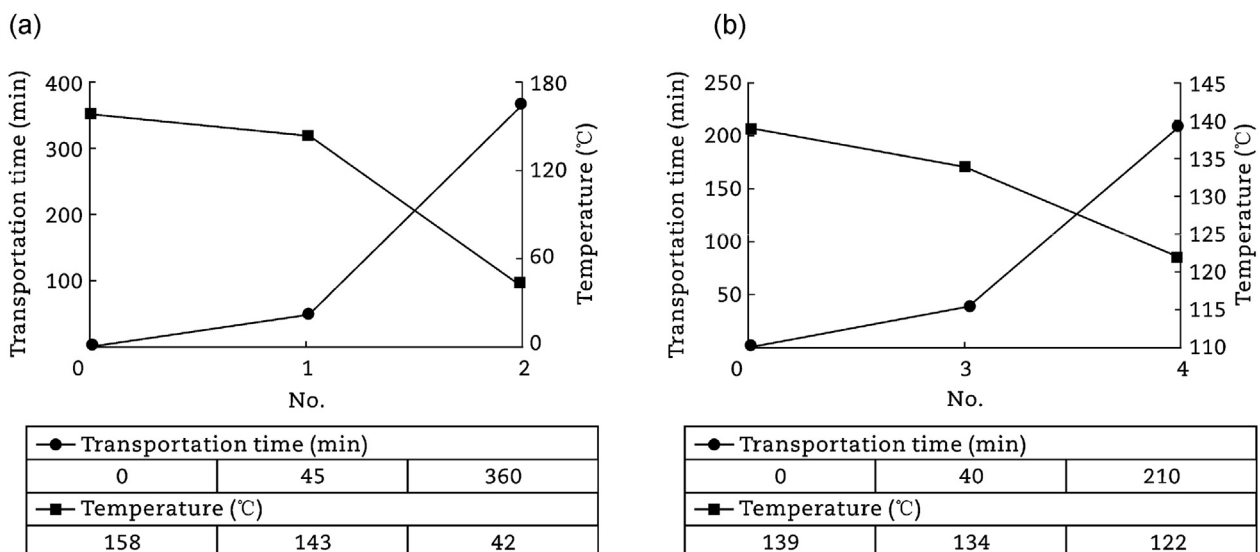
Fig. 10 represents temperature measurements at repair site 2. Four random points were selected to understand the variation in temperature. For each point, seven measurements were collected at different times. Points 1 and 3 were taken on the edges of the mat, and points 2 and 4 were in the middle area of the mat. The measurements

**Fig. 8 – Temperature variation of patch repair on paving site 1 after compaction—thermal image 1.**

showed that different locations of the mat exhibit different repair quality. This means that the points with low temperature are expected to have been poorly compacted creating areas of future premature failure. The points located on the edges (points 1 and 3) had lower temperatures than those located in the middle of the mat (points 2 and 4). The temperature reduced, after 21 min reaching a temperature difference of 56.4 °C for point 1 from the first thermal image shot, 30.6 °C for point 2, 53.3 °C for point 3, and 32.9 °C for point 4 (Table 6). This means that the average percentage of temperature reduction on the edges was approximately 50% and it was approximately 29% in the middle. Consequently, the edges of the repair appear to have a temperature difference of approximately 28% from the middle of the mat, indicating low interface bonding between the host pavement and the hot-fill material which may lead to premature failure of the repair at its edges.

4.2.2. Contractor B

Contractor B was followed during the pothole repair at a single site. Fig. 11 presents the compacted new HMA pothole mix. The

**Fig. 7 – Temperature variation and transportation time of HMA between asphalt production facilities and each repair site. (a) Day 1 repair sites 7–8. (b) Day 2 repair sites 9–10.**

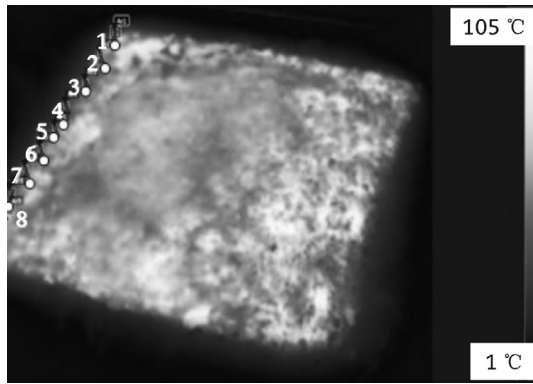


Fig. 9 – Temperature variation of patch repair on paving site 1 after compaction—thermal image 2.

Table 4 – Temperatures measurements of points 1–11 at Fig. 8.

No.	Temperature (°C)
Point 1	38.3
Point 2	60.3
Point 3	90.5
Point 4	34.9
Point 5	39.5
Point 6	92.8
Point 7	73.7
Point 8	50.7
Point 9	80.2
Point 10	85.0
Point 11	46.5

image gives an indication of the overall temperature variation of the mix immediately after compaction. Three points (Points 1, 2 and 3) were studied in more detail. Point 1 was situated away from the kerb line and drainage area. Point 2 was located near the kerb line and within the drainage area and, finally, Point 3 was located at the edge between the new and old reinstatement. Further, due to the position of the repair water was flowing through the patch constantly. Eight temperature recordings were collected for each point all these displayed in Table 7. All points had an initial temperature of approximately 100 °C. This is a 42 °C drop from the initial temperature of 142 °C when the HMA was loaded onto the truck.

Table 5 – Maximum and minimum temperature measurements of points 1–8 at Fig. 9.

No.	Maximum (°C)	Minimum (°C)	Average (°C)
Point 1	43.2	27.8	35.5
Point 2	57.9	49.7	53.8
Point 3	51.1	48.7	49.9
Point 4	42.8	33.3	38.1
Point 5	53.5	44.9	49.2
Point 6	50.0	40.3	45.2
Point 7	48.4	39.9	44.2
Point 8	44.8	33.6	39.2

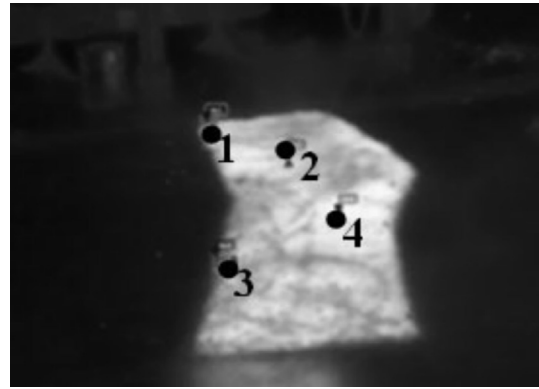


Fig. 10 – Thermal image of patch repair immediately after compaction on paving site 2.

Table 6 – Temperature measurements of points 1–4 at Fig. 10.

Thermal image No.	Time	Temperature (°C)			
		Point 1	Point 2	Point 3	Point 4
1	15:34	109.1	109.1	109.1	109.1
2	15:36	101.2	107.0	100.5	101.5
3	15:37	95.5	104.0	95.0	98.0
4	15:39	84.0	94.0	85.0	90.0
5	15:40	72.0	86.3	75.3	89.0
6	15:43	61.0	84.0	66.8	81.7
7	15:45	52.7	78.5	55.8	76.2

The results indicate that, in a period of 5 min, the temperature for points 1, 2 and 3 dropped to approximately 33%, 65%, and 71%, respectively. The highest drop is for points 2 and 3 which are located at the edges of the repair. Similar results were observed for the repair examples of Contractor A,

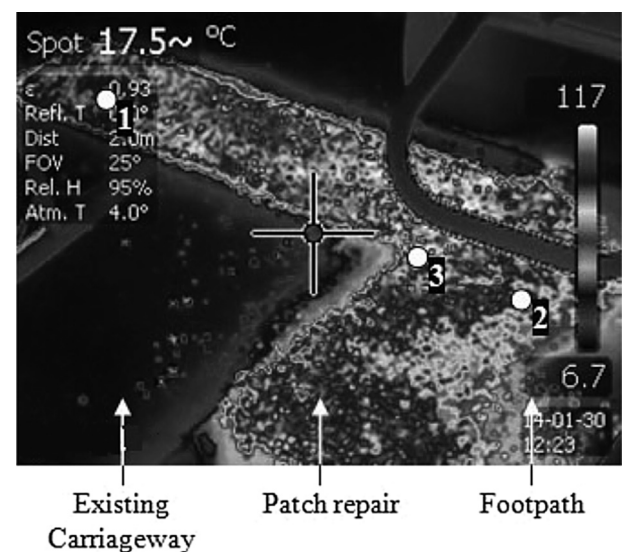


Fig. 11 – Thermal image of patch repair immediately after compaction on repair site 6.

Table 7 – Temperature collection of points immediately after compaction on repair site 6.

Thermal image No.	Time	Temperature (°C)		
		Point 1	Point 2	Point 3
1	12:22	100.0	100.0	100.0
2	12:23	98.0	92.7	81.4
3	12:23	92.0	79.0	75.1
4	12:24	84.6	73.6	73.6
5	12:24	77.1	69.2	57.6
6	12:25	76.6	44.3	39.2
7	12:26	73.8	36.5	33.5
8	12:27	66.7	35.2	29.4

indicating a similar weak point of the executed repairs. Usually, the areas of the repair with a temperature less than the cessation temperature tend to have lower density and cause failure of the patch repair.

4.2.3. Contractor C

In contrast with the other two contractors, temperatures during these repairs were measured on areas and not on specific points. Fig. 12 demonstrates four thermal images for each repair site with temperature variations immediately after compaction. All four repairs had cold spots throughout

the repair area with the lowest temperatures being located at the interface between the host pavements and the new hot-fill material.

Between sites 7 and 8, which were finalized on the same day with site 7 completed first, the thermal images showed quite acceptable levels of temperature for site 7 with an average temperature of 119 °C. However, on site 8 the average temperature was quite below cessation temperature and reached an average temperature of 47 °C. Regarding sites 9 and 10 (completed on the second day) the average temperatures were 62.5 °C for site 9, and 46 °C for site 10, respectively.

4.3. Effect of patch repair process

Patching is an acceptable and well-known method repairing localized distresses on roads such as potholes. It includes marking of the boundaries around the distressed area that indicates the material to be removed, squaring up of the pothole excavation, removal of debris and water, tack coat application which reacts as a bonding agent between existing pavement, and hot-fill material and compaction (Anderson and Thomas, 1984; Lavin, 2003).

At repair sites 1 to 6 no tack coat was used, and at repair site 6 water was present during the preparation of the pothole excavation and the compaction of the new HMA. For repair

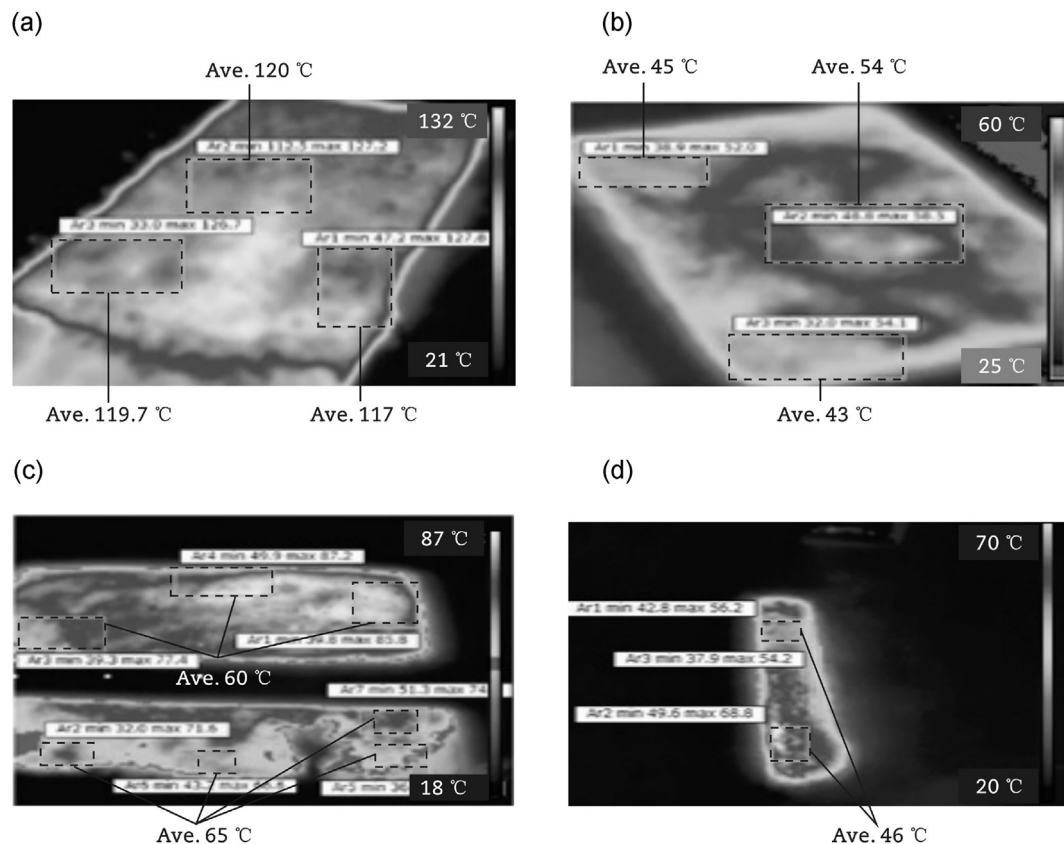


Fig. 12 – Thermal images of patch repairs immediately after compaction. (a) Repair site 7. (b) Repair site 8. (c) Repair site 9. (d) Repair site 10.

site 10, the edge cutting followed the shape of the pothole rather than a more regular boundary.

Factors such as excessive travel time, poor insulation of the hot mix between the production plants and the repair sites, low ambient air and host pavement temperatures, lack of tack coat provision and wet pavement, are expected to adversely affect the service life of the repairs.

5. Revisiting repair sites

All the repaired sites were revisited three months after completion of the repair work. Fig. 13 presents the condition of most of the repairs. The main points of failure were observed along the edges of the reinstatement. Repair site 1 showed also evidence of settlement. Whereas, on repair

sites 6 and 7–10 the patch material had started to fall away. Images (a), (c), (d), (g), and (h) of Fig. 13 demonstrate examples of the points and places where excessive low temperatures were observed after the compaction of the hot-fill material.

6. Observations and conclusions

The main objective of this research was to understand how thermal segregation greatly influenced the overall quality of patch repair work, where the heat losses occurring in transportation of repair material were partly responsible. Three different contractors were studied during their pothole patching using HMA and at ten repair sites. Site observations were analysed for three quality influences (a)

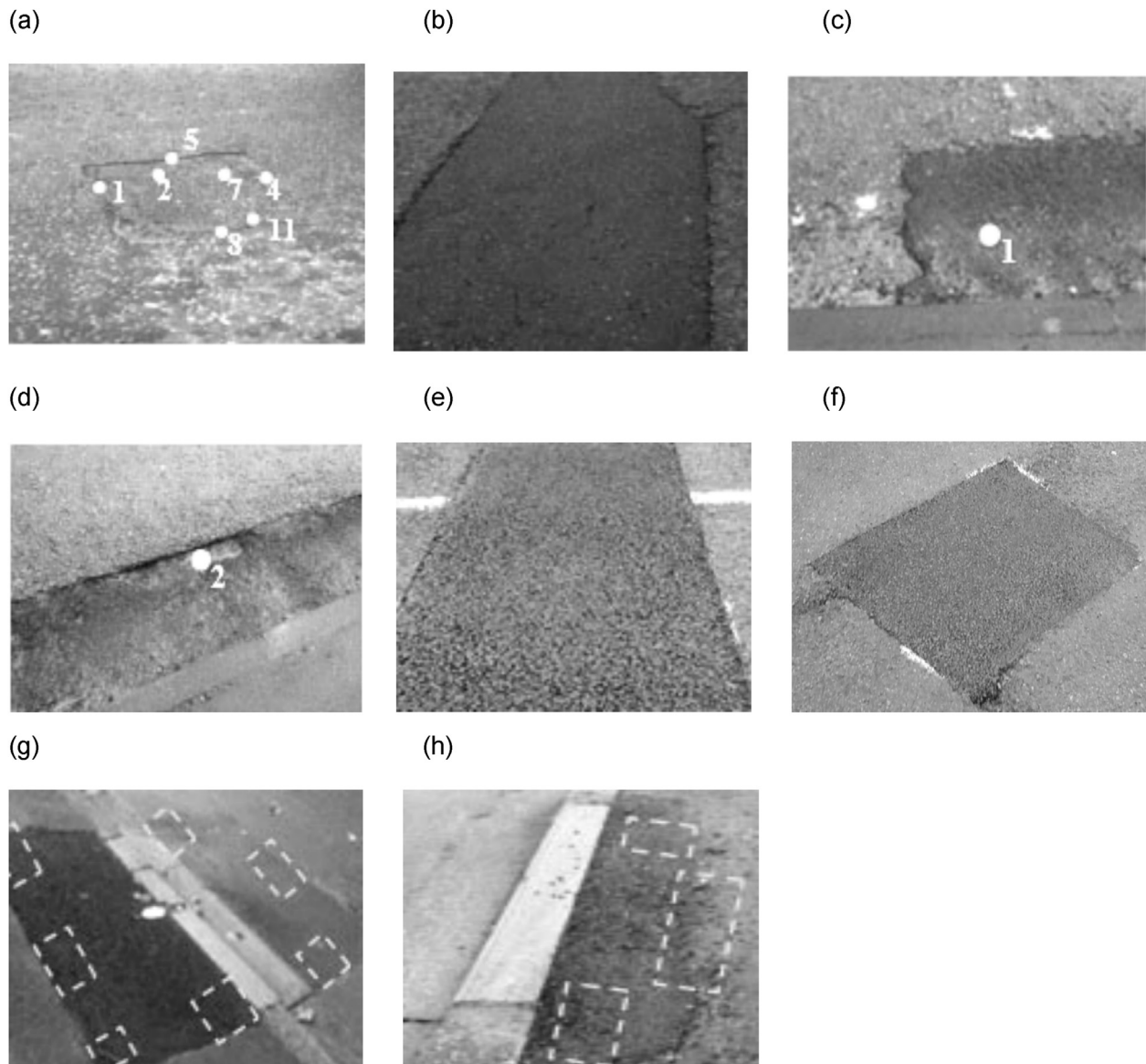


Fig. 13 – Patch repair sites after three months of completion. (a) Repair site 1. (b) Repair site 2. (c) and (d) Repair site 6. (e) Repair site 7. (f) Repair site 8. (g) Repair site 9. (h) Repair site 10.

transportation method, (b) compaction, and (c) repair process.

Thermal segregation was identified for both winter and summer season patch repairs, with wind speed at relatively low levels, from the time that the HMA was collected from the asphalt production facilities, within transportation of the material to the repair sites, and during the laying and compaction processes. It was found that the existing practices for transporting material for minor (patch) repair was poorly controlled, and had a significant impact on the longevity of the repairs. The results showed adverse temperature losses immediately after the material was loaded onto the truck. The heat was escaping through the cover sheet, the joints in the back of the truck as well as alongside the truck.

Cold spots were observed throughout the compacted repair mix, higher temperatures in the middle of the repair and significant low temperatures at the interface between the host pavement and the new hot mix. Low interface temperatures result usually in low density at the repair edges that are prone to water ingress and premature failure. A repeat visit, after three months, revealed premature failures in the areas where the temperature had dropped below the cessation temperature. The deterioration was higher at the edge than at the center at all ten repair sites.

Analysis of the patch repair process also showed that the process can become challenging when the intended repair is in such position that water exists during the actual compaction or the repair is near the kerb. The latter observed mainly on repair sites 6, 9 and 10. The width and the depth of the patch repair affect negatively the compaction process and time available to compact respectively. The former happens when the patch is much smaller than the area of the roller or the plate compactor. This observed on repair sites 1 and 8–10. The latter was observed on all repair sites as the depth ranged at 0.04 m–0.06 m.

To offset the described effects, it would be necessary to plan a days repair work, taking into account the cooling characteristics of the transported repair asphalt relative to ambient temperature, distance and probably travelling time between sites, host pavement temperatures at each site relative to arrival time and anticipated repair time at each site. Without these considerations, there is a risk of repair temperatures below cessation temperature. It would be advantageous to heat the pothole excavation but this must be in a controlled manner.

7. Future work

Ongoing research includes laboratory study of suitable heating regimes for the empty pothole excavation, addressing particularly the pothole perimeter. This is a significant factor in the premature failure for all the repairs presented in this paper. The authors intend to ensure better repair performance and are currently investigating the use of infrared technology for pothole excavation heating prior to placing and completing the hot repair.

The study includes heat analysis of the pothole excavation and internal fill mass for both shallow and deep potholes, this based on measurement of thermal properties for the host pavement and a range of asphalt fill mixes. Wheel truck tests of preheated and non-heated pothole repairs, as well as bond strength tests of the boundary of the executed repairs, are being applied to quantify repair performance.

Acknowledgments

We acknowledge the contribution from final year students: Tavengwa Goya, Danny Weston-Brown and Derrick Kigozi.

REFERENCES

- Adlinge, S.S., Gupta, A., 2013. Pavement deterioration and its causes. *International Journal of Innovative Research and Development* 2 (4), 437–450.
- Anderson, D.A., Thomas, H.R., 1984. Pothole Repair in Pennsylvania. Available at: <http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3367&context=roadschool&sei-redir=1&referer=http%3A%2F%2Fen.bing.com%2Fsearch%3Fq%3DPothole%2BRepair%2Bin%2BPennsylvania%26go%3D%25E6%25F%2590%25E4%25BA%25A4%26qs%3Dn%26form%3DQLBH%26pq%3Dupper%2Bgreat%2Bplains%2Btransportation%2Binstitute%252C%2Bnorth%2Bdakota%2Bstate%2Buniversity%26sc%3D0-74%26sp%3D-1%26sk%3D%26cvid%3D7F3F029B98464C039DC75F74BDC9A508#search=%22Pothole%20Repair%20Pennsylvania%22>. (Accessed 7 February 2016).
- Asphalt Industry Alliance, 2015. Key Findings of Asphalt Industry Alliance-2015 Annual Local Authority Road Maintenance (ALARM SURVEY). Available at: <http://www.asphaltindustryalliance.com/alarm-survey.asp>. (Accessed 7 February 2016).
- Bode, T.A., 2012. An Analysis of the Impacts of Temperature Segregation on Hot Mix Asphalt. University of Nebraska – Lincoln, Lincoln.
- Davis, J., 2012. Infrared system detects thermal segregation. *Asphalt* 27 (2), 37–41.
- Dawson, A., 2008. Water in Road Structures: Movement, Drainage and Effects. Springer Science & Business Media, Dordrecht.
- Delgadillo, R., Bahia, H.U., 2008. Effects of temperature and pressure on hot mixed asphalt compaction: field and laboratory study. *Journal of Materials in Civil Engineering* 20 (6), 440–448.
- FLIR Systems AB, 2011. Thermal Imaging Guide Book for Building and Renewable Energy Applications. Flir Systems AB, Wilsonville.
- Hartman, A., Gilchrist, M., Walsh, G., 2001. Effect of mixture compaction on indirect tensile stiffness and fatigue. *Journal of Transportation Engineering* 127 (5), 370–378.
- Kloubert, H., 2009. Basic Principles of Asphalt Compaction: Compaction Methods, Compaction Equipment, and Rolling Technique. Available at: http://www.bomag.com/world/media/pdf/PRE109016_0901.pdf. (Accessed 7 February 2016).
- Knapman, C., 2013. Britain's Pothole Problem Deepens. Available at: <http://www.telegraph.co.uk/motoring/road-safety/9927061/Britains-pothole-problem-deepens.html>. (Accessed 7 February 2016).
- Lavin, P., 2003. Asphalt Pavements: a Practical Guide to Design, Production and Maintenance for Engineers and Architects. CRC Press, Boca Raton.
- Rahman, M., Thom, N., 2012. Performance of Asphalt Patch Repairs. Institute of Civil Engineers, London.

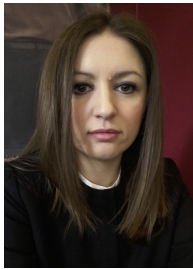
Stroup-Gardiner, M., Brown, E., 2000. Segregation in Hot Mix Asphalt Pavements. National Cooperative Highway Research Program (NCHRP). Report 441. Transportation Research Board, Washington DC.

Texas Department of Transportation, 2011. Manual Notice, Pavement Design Guide. Available at: <http://onlinemanuals.txdot.gov/txdotmanuals/pdm/index.htm>. (Accessed 7 February 2016).

The Automobile Association (AA), 2016. Potholes: Plummeting Road Condition Leaves Drivers Deeper in Trouble. Available at: <http://www.theaa.com/newsroom/news-2014/potholes-road-condition-survey-2014.html>. (Accessed 6 February 2016).

Thom, N., 2008. Principles of Pavement Engineering. ICE Publishing, London.

Watson, D.E., West, R.C., Turner, P.A., et al., 2010. Mixing and Compaction Temperatures of Asphalt Binders in Hot-mix Asphalt. The National Academies Press, Washington DC.



Juliana Byzyka has been a PhD student and teaching assistant in the Department of Mechanical, Aerospace and Civil Engineering of Brunel University London since December 2015. Her past studies include MSc in advanced engineering design and BEng (Hons) in civil engineering. Her main research areas can be summarised as pavement engineering, patch repair failures on asphalt pavements, use of infrared technology in patching operations for improving the

performance of pothole repairs and simulation modelling of pothole heating and repair process. In the early stages of her PhD one of her research papers has gained a Best Paper Award.



Mujib Rahman is a chartered engineer and a senior lecturer in civil engineering at Brunel University London. He has more than 15 years professional experience and has gained extensive research experience on the fundamental characterisation of asphalt and concrete materials, non-destructive based evaluation of civil engineering in-

frastructures, and protection of porous construction materials. He is author/co-author of over 70 highly regarded international journals and conference articles and has also written over 100 design and consultancy reports for government departments and private organisations. His research is sponsored by EPSRC, EC, DfT, Highways Agency, Institution of Civil Engineers and private organisations.



Denis Albert Chamberlain, fellow member of the Institution of Civil Engineers, has 21 years' experience as a civil engineering contractor and consultant in the UK and abroad. This combines with 27 years' service as a university professor in building research groups addressing a range of industrially relevant problems. He has five patents for his inventions and has authored and co-authored numerous papers dealing with construction materials and their application.

The effect of application time adverse climatic conditions on the life performance of materials is a particular interest of him. He is currently supervising research of his pot-hole repair heater at Brunel University London.